

SIMULATION OF MULTIPACTING IN SC LOW BETA CAVITIES AT FNAL*

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Abstract

Proton Improvement Plan-II at Fermilab is a plan for improvements to the accelerator complex aimed at providing a beam power capability of at least 1 MW target at the initiation of LBNE (Long Base Neutrino Experiment) operations. The central element of the PIP-II is a new 800 MeV superconducting linac, injecting into the existing Booster. Multipacting affects superconducting RF cavities in the entire range from high energy elliptical cavities to coaxial resonators for low-beta applications. This work is focused on multipacting study in the low-beta 325 MHz spoke cavities; namely SSR1 and SSR2, which are especially susceptible to the phenomena. The extensive simulations of multipacting in the cavities with updated material properties and comparison of the results with experimental data helped us to improve overall reliability and accuracy of these simulations. Our practical approach to the simulations is described in details. For SSR2, which has a high multipacting barrier right at the operating power level, some changes of the cavity shape to mitigate this harmful phenomenon are proposed.

INTRODUCTION

Proton Improvement Plan-II [1] at Fermilab is a plan for improvements to the accelerator complex aimed at providing a beam power capability of at least 1 MW target at the initiation of LBNE (Long Base Neutrino Experiment) operations. The central element of the PIP-II is a new 800 MeV superconducting linac, injecting into the existing Booster. The PIP-II 800 MeV linac is a derivative of the Project X Stage 1 design as described in the Project X Reference Design Report [2]. A room temperature (RT) section accelerates H^+ ions to 2.1 MeV and creates the desired bunch structure for injection into the superconducting (SC) linac. Five superconducting cavity types operating at three different frequencies are required for acceleration to 800 MeV.

The electron multiplication on surfaces exposed to an oscillating electromagnetic field causes the phenomenon of multipacting, which is a serious obstacle to be avoided for normal operation of particle accelerator and their RF components. In worst cases this phenomena, described in many accelerators, can completely prevent normal operation of an accelerating cavity.

Multipacting affects superconducting RF cavities in the entire range from high energy elliptical cavities to coaxial resonators for low-beta applications. This work is focused on multipacting study in the low-beta structures; namely

325 MHz Single-Spoke Resonators: SSR1 ($\beta=0.22$) and SSR2 ($\beta=0.47$).

Study of MP in SSR2 was a primary goal of this work along with sharpening of simulation technique. SSR2 is currently under development for PIP-II linac [3]. The design has been finalized recently, and the preliminary simulations indicated strong MP in the cavity. It was necessary to understand at what level this resonator is affected by multipacting, what critical gradients are, where the MP develops in the cavity geometry and what can be done to mitigate this harmful phenomena.

Multipacting in the SSR1 cavity has been studied already [4], and the results have been compared with experimental data on multipacting barriers found during the vertical test of the SSR1 cavity [5]. In this work the MP simulations in the SSR1 cavity were repeated by two reasons. First, a new secondary emission yield (SEY) data for niobium became available – the previous simulations of the SSR1 used SEY for copper, that allows defining RF power levels of MP, but is not correct to evaluate intensity and exact boundaries of MP discharge. Second, 12 SSR1 cavities were manufactured and tested at high power level since then, and rich experimental data on the MP behaviour in SSR1 during RF conditioning was accumulated [6]. Comparison of the MP simulations that used updated material properties with experimental data helped us to evaluate overall reliability and accuracy of our simulation technique.

NEW IN SIMULATION SET UP

There are a number of numerical simulation codes for predicting multipactor, each with various pros and cons. Our choice is still CST Studio Suite because it smoothly combines flexible and developed modelling, electromagnetic field simulation, multi-particle tracking, adequate post-processing and advanced probabilistic emission model (Furman-Pivi model [7]), which is very important capability in multipactor simulations. In general we follow earlier established simulation procedure [4, 8] but several new features have been added.

CST Particle Studio (PS) offers two solvers for particle tracking; this time both were used in our MP simulations. One of them is the Gun Solver & Particle Tracking solver (TRK) which is used to compute trajectories of charged particles within RF fields and optionally electrostatic or/and magnetostatic fields. Other one is the Particle-In-Cell solver (PIC) that computes the charged particles motion in self-consistent transient fields. Usually the space charge effects are not taken into account in MP simulations, so just simple particle tracking in electromagnetic fields was used for both solvers.

PIC solver can use only imported field maps, while TRK solver has its own eigenmode solver, but it also can

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use imported fields. For both solvers we use imported field maps that were calculated separately with tetrahedral mesh enhanced near cavity surfaces (see Fig.1). The field maps being imported into PIC and TRK are modified to conform hexahedral mesh used in both solvers for tracking. Though both meshes and exporting grid are dense (mesh cell size was 0.5-1.5 mm near surfaces), there is some field quality deterioration during this operation.

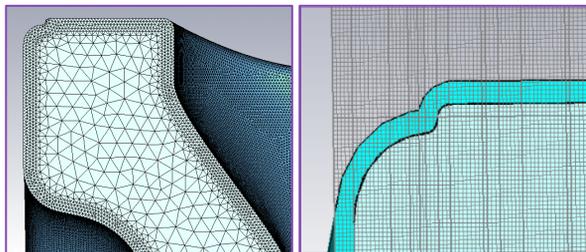


Figure1: Tetrahedral mesh used in eigenmode solver and hexahedral mesh used for tracking.

To reduce total number of meshcells and therefore time of simulations we decided to use 1/8 of the cavity models. Unfortunately there are no boundary conditions in CST PS that simulate mirror reflections of the electrons. We closed symmetry planes of the models with walls and assigned to them the emission properties with 100% reflection and zero true and diffusion secondary emission yield (see Fig.2). These walls do not simulate true mirror reflection since the angle of reflection is still random according to the Furman model, but at least they prevent losses of electrons and their energy.

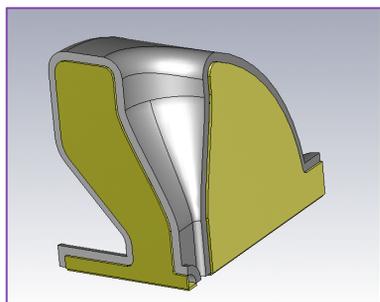


Figure 2: "Mirror" walls in 1/8 cavity model.

For indication of MP and evaluation of its probable intensity we use averaged secondary emission yield $\langle \text{SEY} \rangle$, energy of collision and exponential growth rate coefficient α defined as

$$\langle \text{SEY} \rangle = \frac{I_{\text{emission}}}{I_{\text{collision}}}; \quad W_{\text{collision}}(eV) = P_{\text{collision}}(W) / I_{\text{collision}}(A);$$

$$N(t) = N_0 e^{\alpha t}; \quad \langle \text{SEY} \rangle = e^{\alpha T},$$

where t is time of simulation, T – RF period, N_0 – initial number of particles. Other parameters are standard CST PS output averaged over last 3-5 RF periods. Earlier we defined $\langle \text{SEY} \rangle$ as a ratio of number of secondary electrons to number of impacts. The latest versions of CST PS generate collision and emission currents instead of these numbers. With respect to that a pulse of initial

particle current in PIC solver should be as close to rectangular shape as possible to avoid big difference in charges of macroparticles. The problem is that the source in PIC solver generates pulse of particle that is Gaussian in time regarding to emitted current, while the number of emitted particles vs time is constant.

If multipacting simulations performed properly the TRK and PIC solvers deliver almost the same results as it is shown in Fig.3. The choice between the two depends on the particular needs: TRK solver is simpler and faster, while more flexible PIC solver has well developed post-processing, but may be very slow.

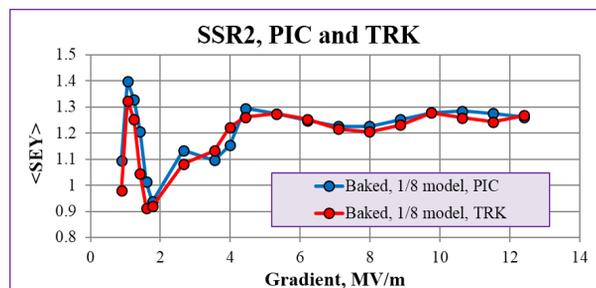


Figure 3: Comparison of PIC and TRK solvers.

MULTIPACTING IN SSR1

The MP simulations in SSR1 presented here were performed with PIC solver and the material emission properties corresponding to baked niobium. The result is very similar to that obtained with TRK solver and annealed copper [4, 8]. The repeated simulations are much more thorough (and much more time consuming). They are in excellent agreement with experimental statistic data (see Fig.4).

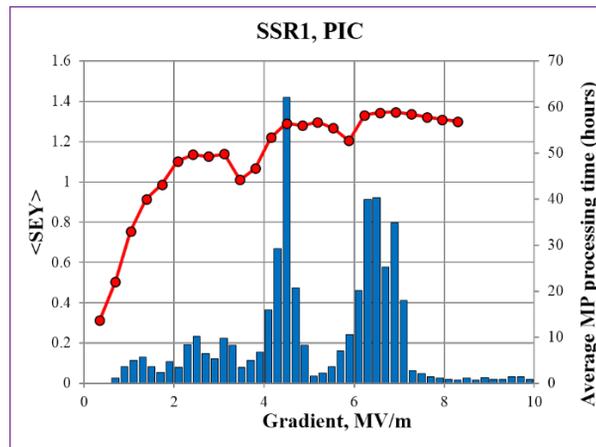


Figure 4: Simulated MP barriers and average processing time required to get through the barriers.

A finer structure of MP – three barriers instead of two – has been revealed in the simulations. First barrier is a non-resonant MP at low gradients in $\approx 0.9-3.5$ MV/m interval. This barrier is rather broad, but not intense, so it was not a problem in terms of processing time. Next two barriers are intense resonant MP of 1-3 orders. Each barrier is associated with MP in different areas of SSR1

cavity (see Fig.5), though the areas are pretty much overlapped.

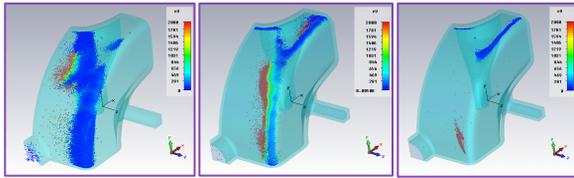


Figure 5: MP locations associated with the barriers.

MULTIPACTING IN SSR2

Original design of SSR2 cavity showed high risk of multipacting – in simulations $\langle \text{SEY} \rangle$ exceeds 1.2 in the broad interval of accelerating gradients even for discharge cleaned niobium [8]. Keeping in mind the very good agreement between simulations and practice for SSR1, we took this prediction seriously and decided to study different geometry changes to mitigate this phenomenon.

We studied a number of SSR2 geometry modifications trying to reduce risk of MP and keep the accelerating parameters intact at the same time. The simulations were performed with PIC and TRK solvers, using two different surface finish of material – baked niobium (higher SEY) and discharge cleaned niobium (lower SEY).

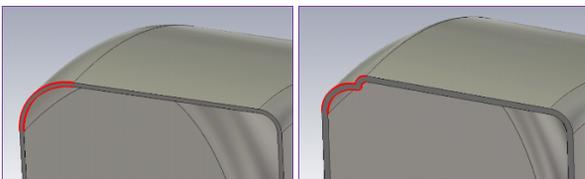


Figure 6: Proposed geometry change in SSR2 cavity.

The most effective variant that we found includes double-radius corners (see Fig.6). This main feature of the geometry does not actually suppress multipacting. It changes resonance conditions of MP, splitting main resonance and making overall process less intense and flattened (see Fig.7). The result with discharge cleaned niobium is even better than for SSR1 with the same surface treatment, which is encouraging fact, taking into account that we routinely achieve that level of surface finish. No side effects that would degrade accelerating efficiency were found so far.

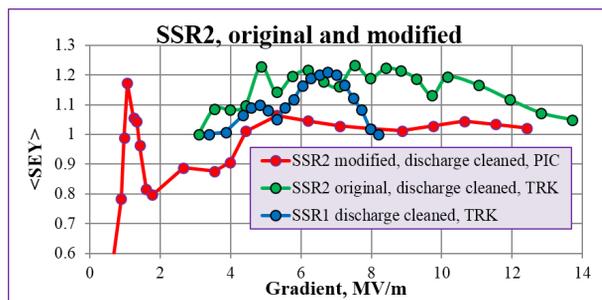


Figure 7: Reduced $\langle \text{SEY} \rangle$ in modified SSR2 cavity compared to the original design and SSR1.

The simulations with different surface finish confirmed the conclusion made in [9] that the simulations with

material with higher SEY are sufficient and preferable, because the simulating time is reduced since MP develops faster, and the simulations are more stable and consistent. The resulting $\langle \text{SEY} \rangle$ curve for low emissive material would be similar and just accordingly lower (see Fig.8).

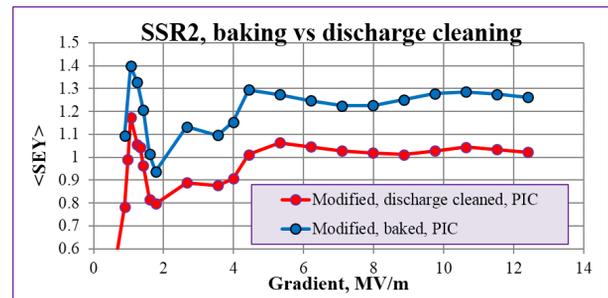


Figure 8: The simulations of MP in SSR2 with different surface treatment.

CONCLUSION

The simulations of multipacting in SSR1 with enhanced accuracy demonstrated very good agreement with experimental statistical data. The proposed geometry changes in SSR2 to mitigate intense multipacting were proved to be effective. Additional study will be conducted to avoid any possible side effects that could degrade cavity performance.

It was shown that PIC and TRK solvers can deliver equivalent results. Also it was confirmed that the simulations with higher emissive materials are preferable for comprehensive and faster multipacting study.

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